Sensing and Awareness in Microsystems

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Harsh Environment Wireless MEMS
Sensors for Energy & Power

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Presentation Outline

Harsh Environment Wireless MEMS

- Acknowledgements
- Research Motivation
- High Temperature Sensors
- Materials for Harsh Environments
- Future Vision 1: Passive Telemetry
- Future Vision 2: Active Telemetry
- Conclusions

Acknowledgements

Harsh Environment Wireless MEMS

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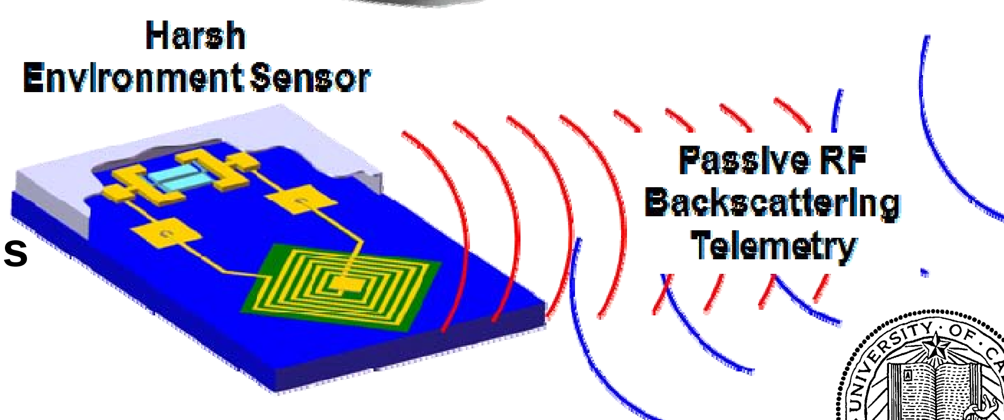
- Prof. Bernhard Boser (UCB)
- Dr. Ken Wojciechowski
- Dr. Jan H. Kuypers
- Dr. Debbie G. Senesky
- Dr. Babak Jamshidi
- Mr. David Myers
- Mr. Benjamin (Kan Bun) Cheng
- Mr. Matt Chan
- Mr. Ryan Xie
- Mr. Gabriele Vigevani
- Ms. Sarah Wodin-Schwartz
- Mr. Jonathan Rheaume

Research Motivation

Harsh Environment Wireless MEMS

- **Next generation power systems**
  - **Reduced emissions**
  - **Increased efficiency**
  - **Fuel flexibility**
  - **Greater bandwidth**
- **Real-time monitoring and control of power systems**
  - **Enable condition based monitoring**
  - **Predict failure of materials and critical components**
  - **Prevent combustion instabilities**
  - **Reduce NO_x and CO_2**
- **Harsh environment telemetry is one solution for obtaining control data for combustion systems.**

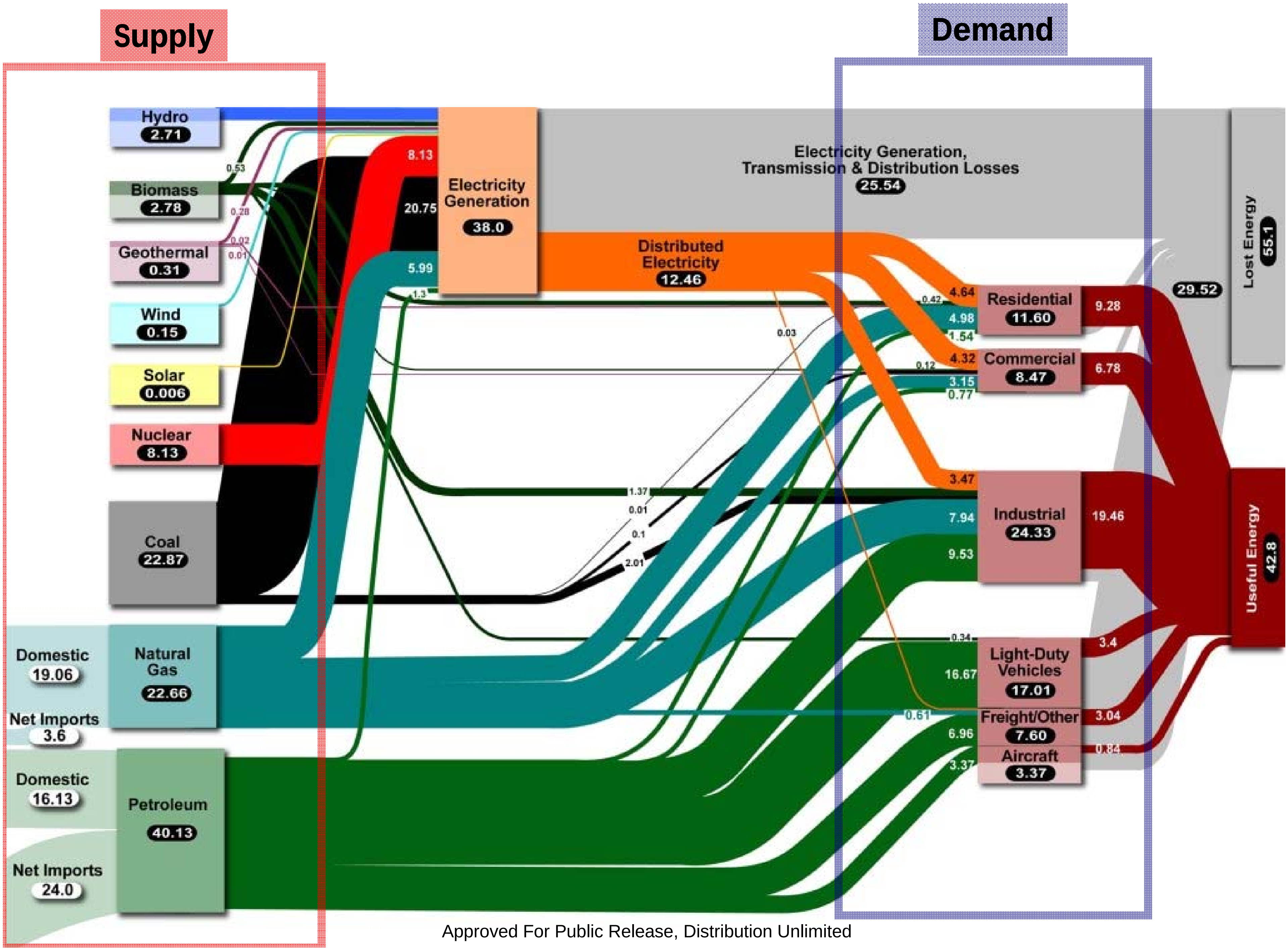
Automotive Engines



Technology Trend Analysis

Harsh Environment Wireless MEMS

- **Energy sources will diversify**
  - Specific solutions for specific problems
  - Avoid problems with scaling single solutions
- **Advanced combustion will play a role**
  - Highest specific power
  - Existing infrastructure
- **THEREFORE ---**
- **Sensors required for more efficient power generation**
- **Energy scavenging required for active sensors systems**



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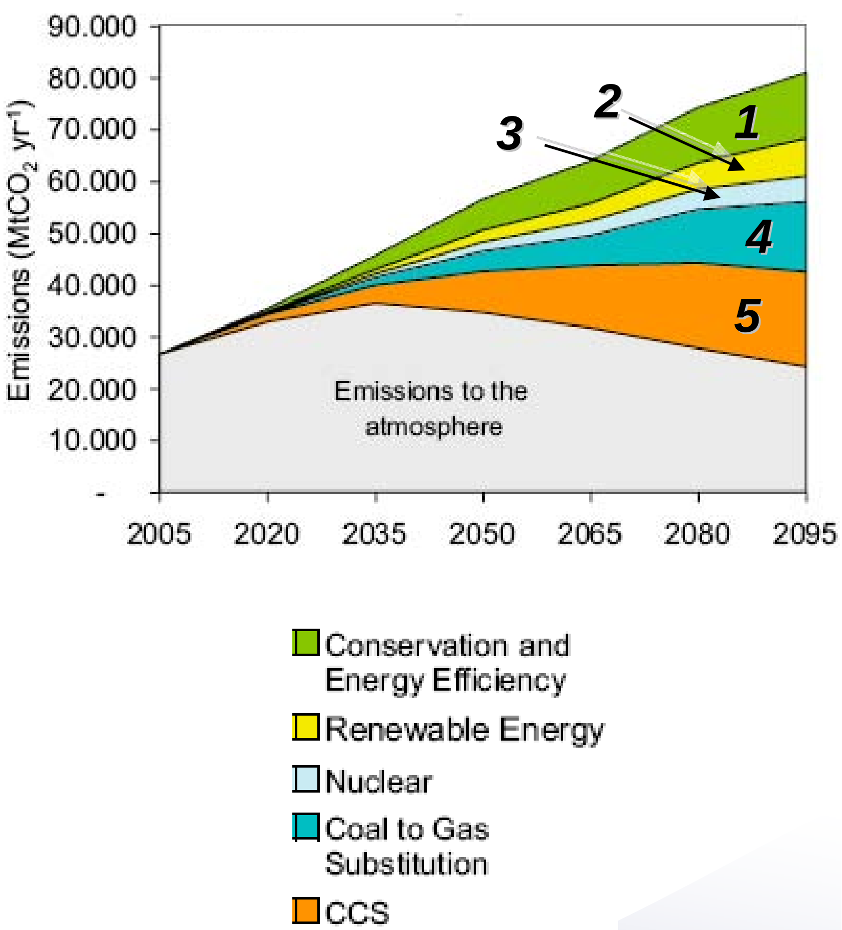
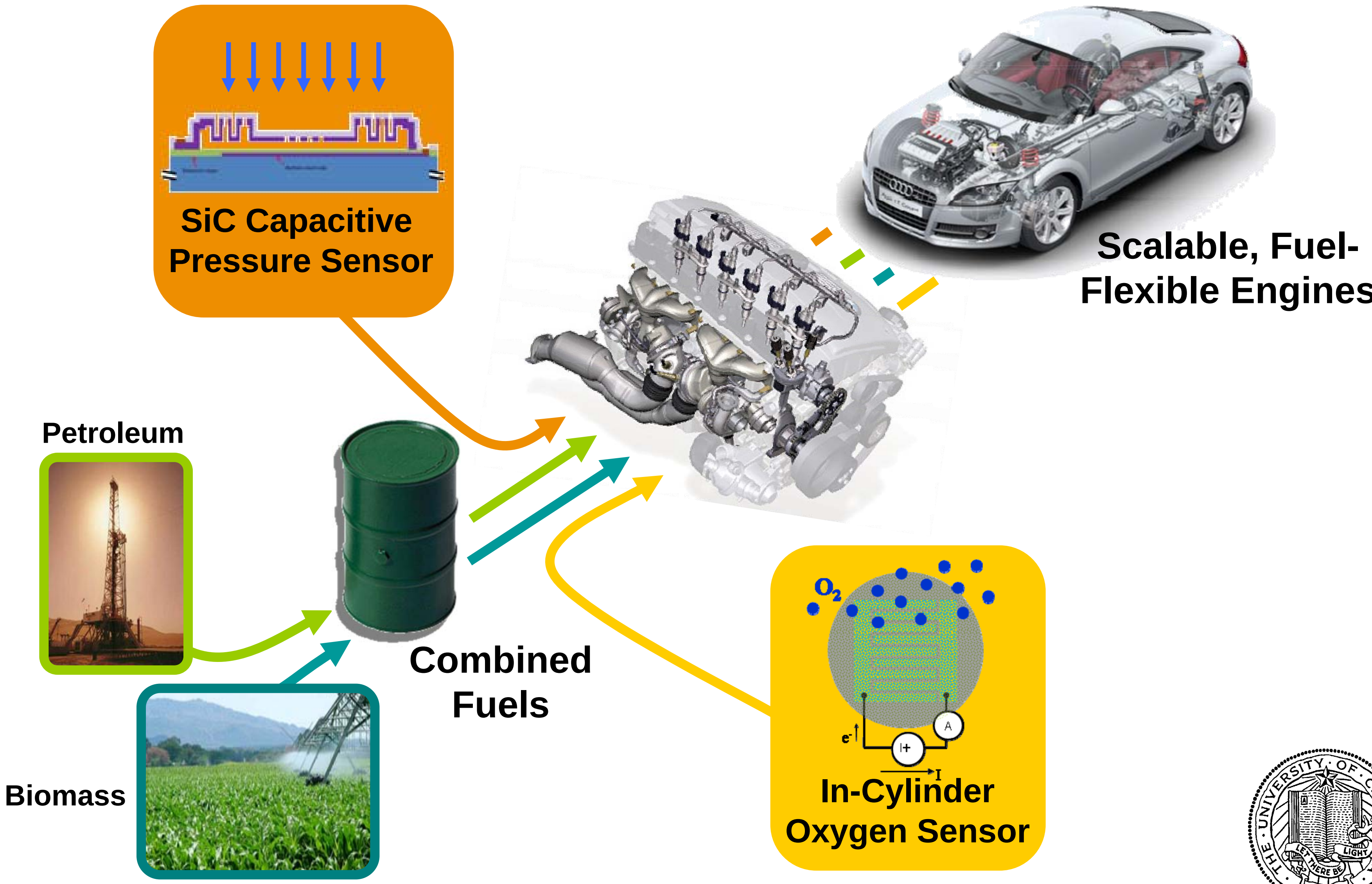
The CITRIS Solution: “Conservation” plus “Creation without Carbon Emissions”

1. ***Conservation & Energy Efficiency***
   - ***Power-Aware Buildings***
   - ***Fuel Efficiency***
   - ***Sustainable Transportation***
2. ***Renewable Energy***
   - ***Alternative Fuels***
   - ***Alternative Power***
3. ***Nuclear Energy***
4. ***Coal to Gas Substitution***
5. ***Carbon Capture & Storage***



Mobile Power Sources

Harsh Environment Wireless MEMS



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Stationary Power Sources

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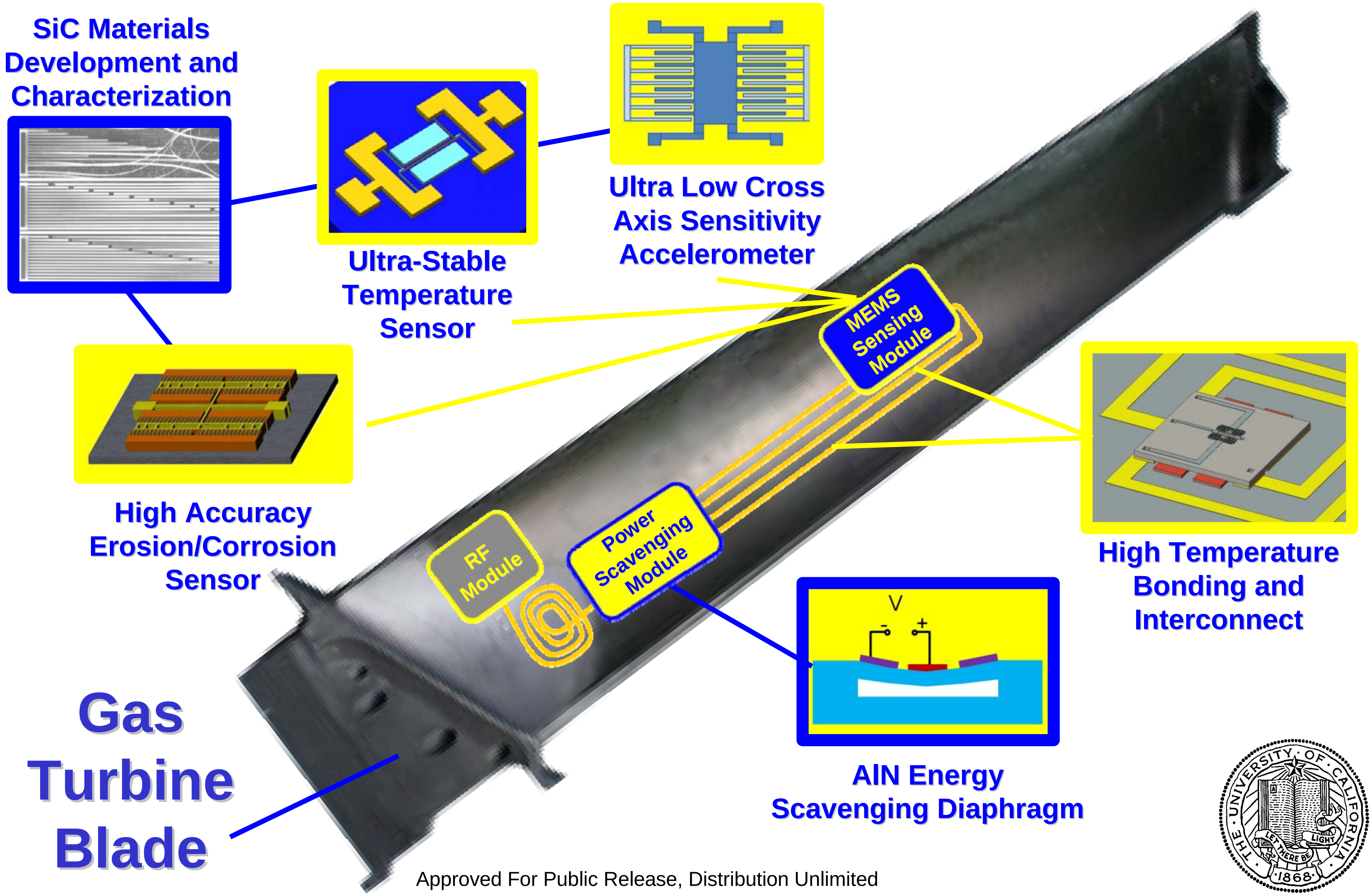
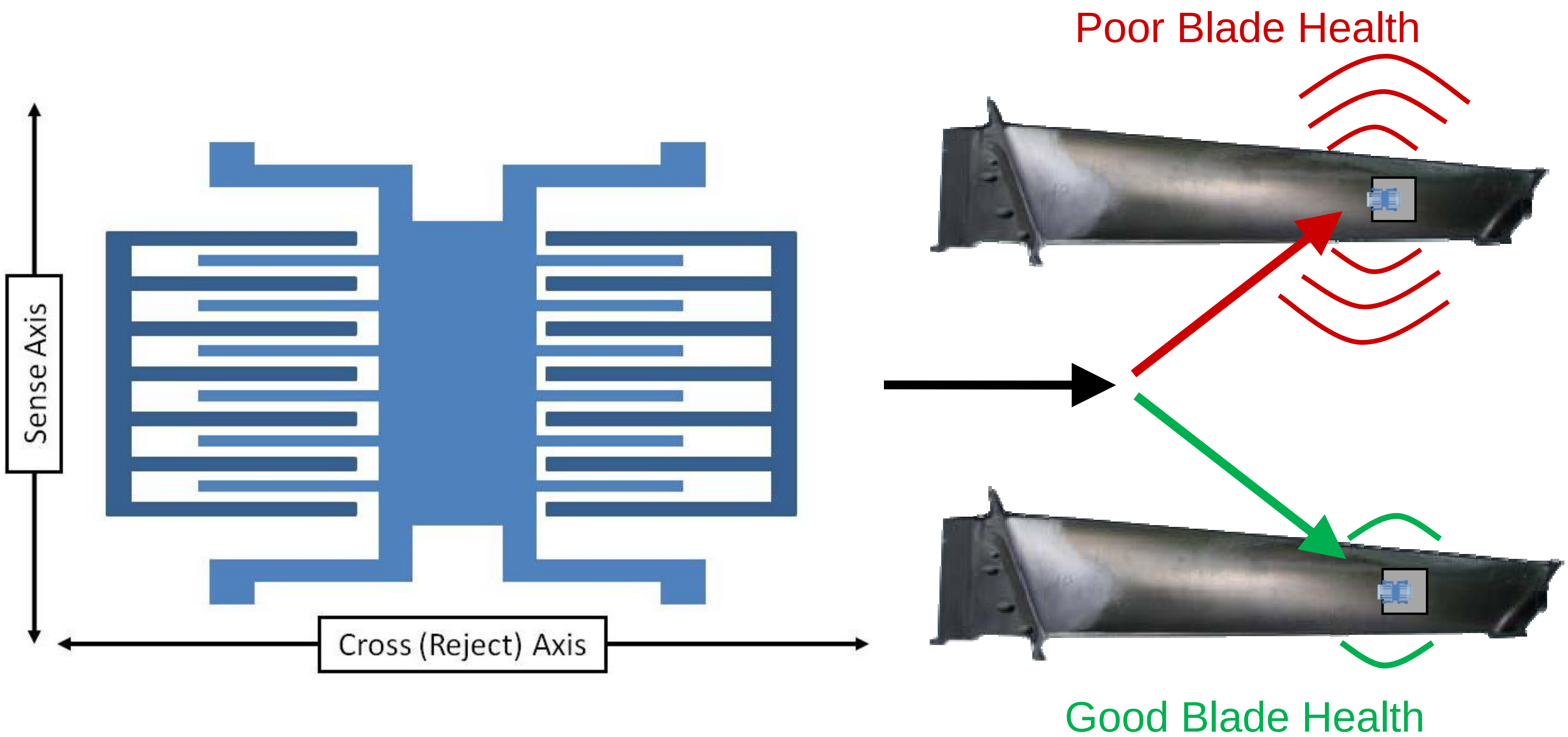


SiC Accelerometer

Harsh Environment Wireless MEMS

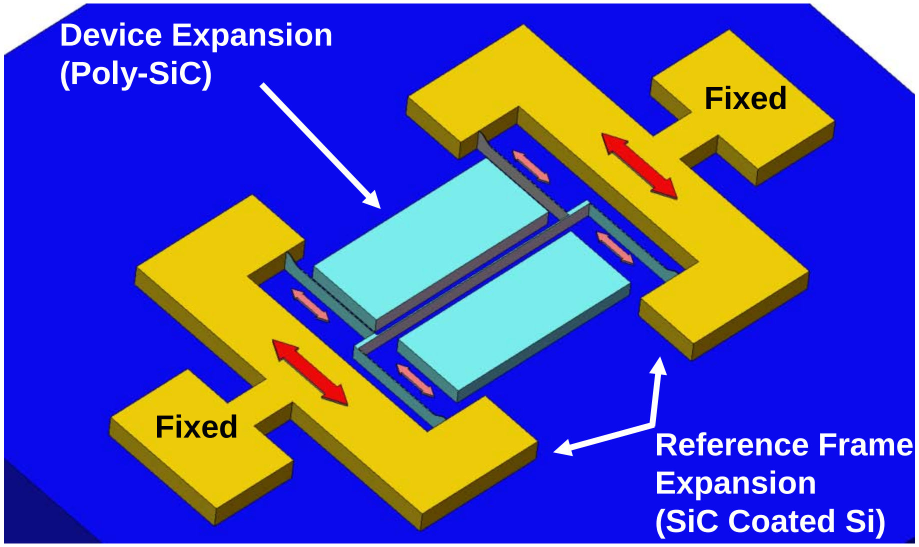


- **Abnormal vibrations indicate blade cracking and occur before potential failure**
- **Ultra low cross axis sensitivity accelerometer can be used to detect abnormal vibrations**

Poster #95: D. Myers

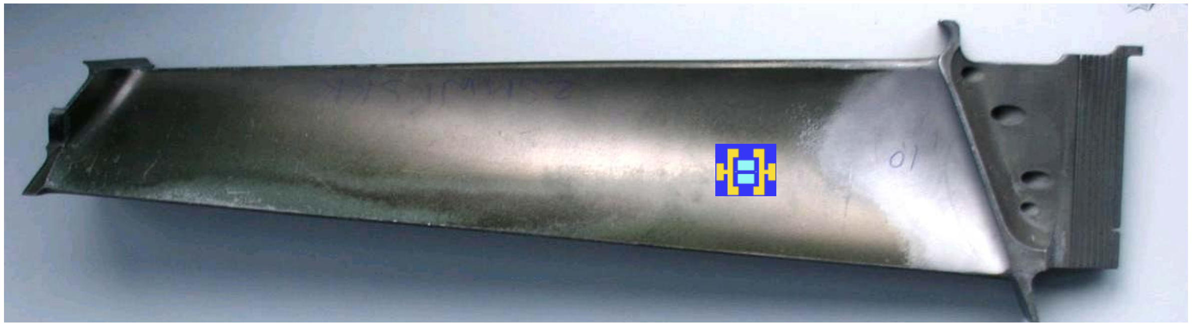
SiC Temperature Sensor

Harsh Environment Wireless MEMS



A capacitive temperature sensor which works based on the thermal coefficient of expansion mismatch between Silicon and Silicon Carbide structures.

- Intrinsically temperature insensitive
- Low power
- Highly accurate and stable
- Requires traditional circuitry
- Mechanically decoupling strain and temperature effect

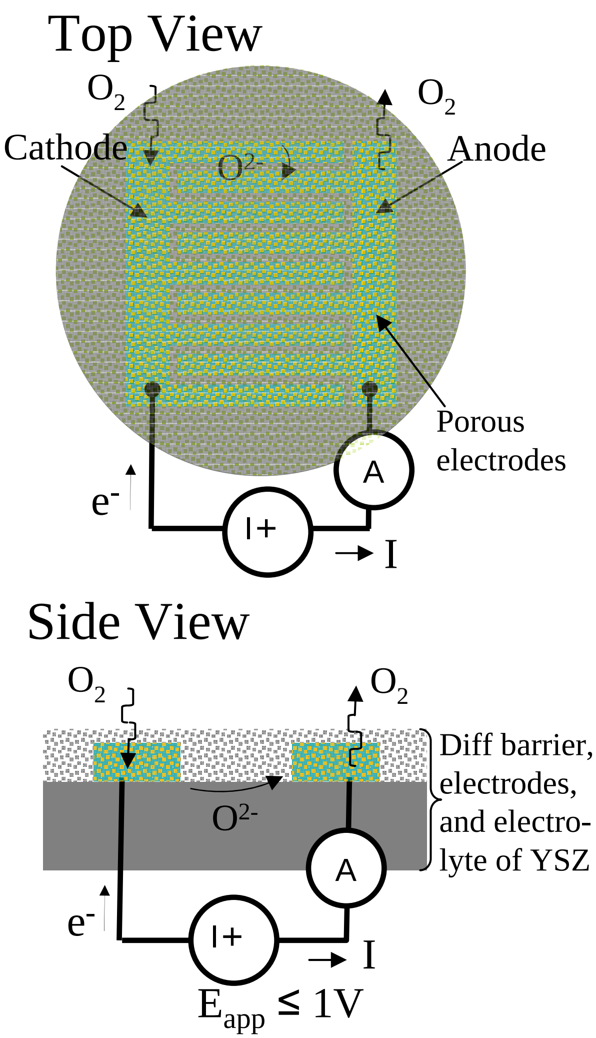


Temperature sensor attached on the blade

Poster #94: D.G. Senesky

Microscale YSZ O_2 Sensor

Harsh Environment Wireless MEMS



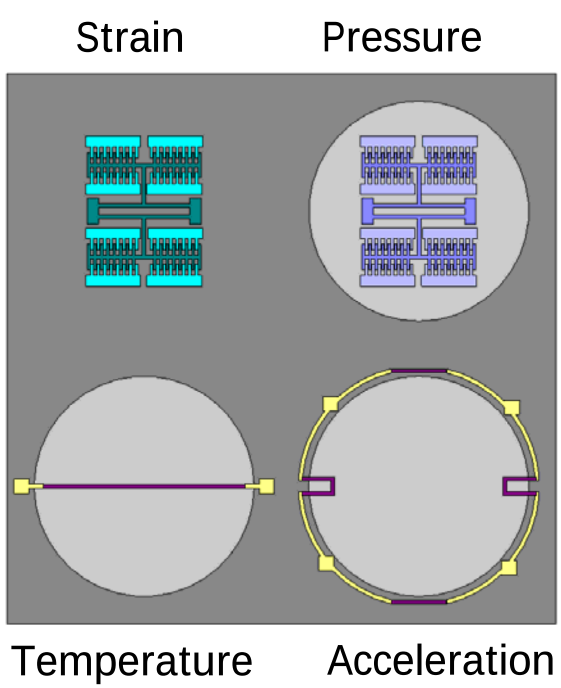
Features	Benefits
Electrodes on same side	allows utilization of microfabrication techniques including microprinting
Interdigitated electrodes	increase reaction sites and ion conduction flux area
Short channel length	facilitates rapid ion exchange for fast response
YSZ electrolyte/substrate	mitigates thermal stresses
Electrolyte, electrodes, and diff barrier of YSZ	better matches CTEs
30% Pt/YSZ cermet electrodes	increases triple phase boundary; 3YSZ and Pt CTE match at high T
Porous electrodes	allows transport and O_2 evolution, creates large surface area for reactions, and alleviates stress
Co-fired electrodes, substrate and diff barrier	mitigates stress from CTE mismatch

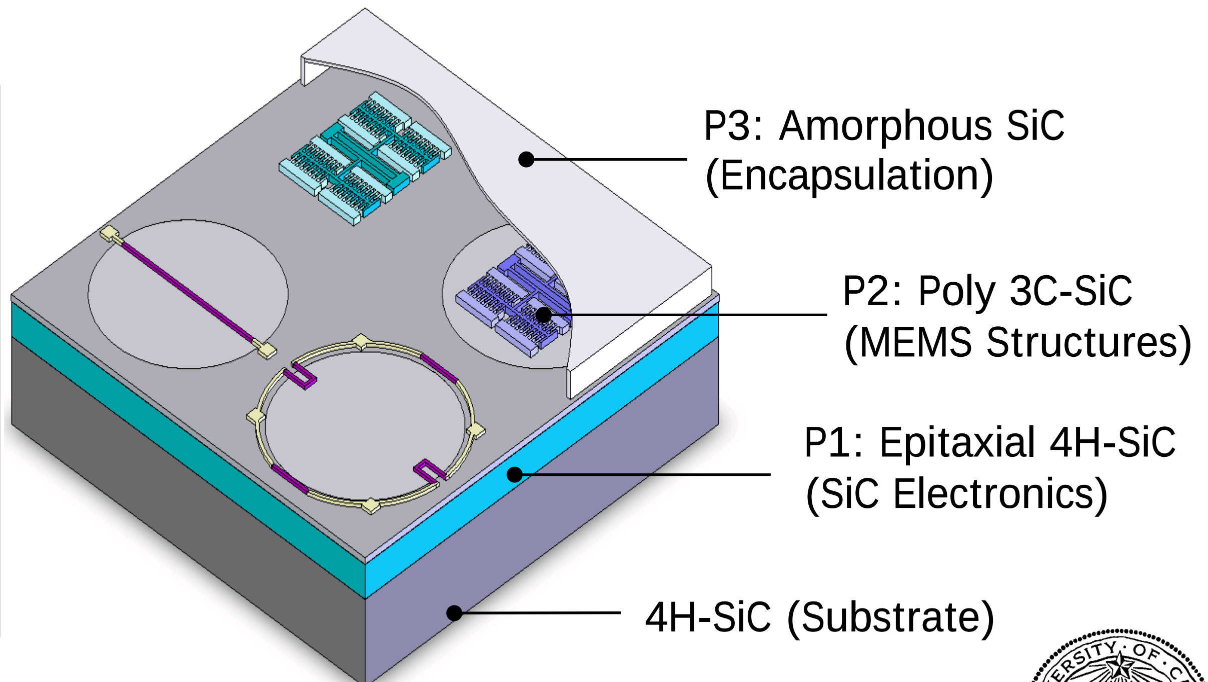
Poster #52: J. Rheaume

SiC TAPS Project

Harsh Environment Wireless MEMS

- **Development of extreme harsh environment TAPS (<u>T</u>emperature, <u>A</u>cceleration, <u>P</u>ressure, and <u>S</u>train) sensors on a single chip**
- **Silicon carbide (SiC) as a platform material (Electronics, MEMS, and Encapsulation)**





Poster #94: D.G. Senesky

Harsh Environment Specifications

- **Instrumentation Requirements:**
  - **Elevated temperatures (600°C)**
  - **Elevated pressures (up to 1000 psi)**
  - **High g-shock**
  - **Corroding and oxidizing environments**
  - **New materials systems**
    - **Barrier coating materials**
    - **High temperature base metals**
- **Candidate Materials**
  - **Silicon is limited to temperatures below 350˚C**
  - **Silicon Carbide (SiC) sensors have demonstrated operation at 600˚C**
  - **Aluminum Nitride (AlN) can operate at temperatures above 1000˚C**
    - **Non-ferroelectric material**
    - **Piezoelectric actuation**
    - **RF communication**
    - **Compatible etch mask**
    - **Hexagonal crystal structure**

Material Properties

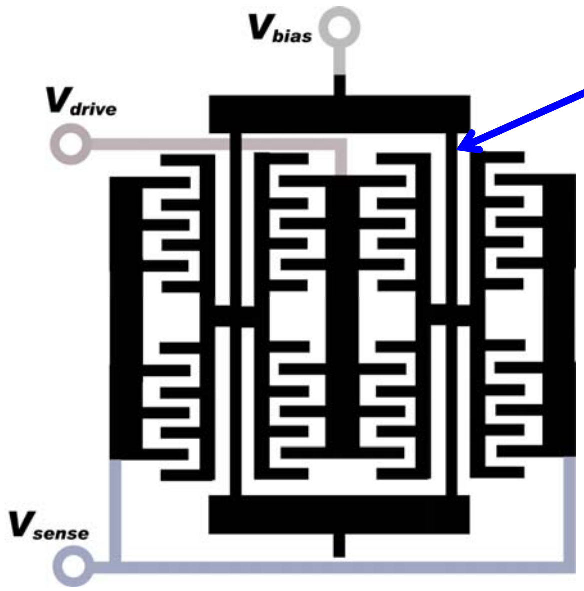
Harsh Environment Wireless MEMS

Property	Silicon Carbide 3C-SiC (6H-SiC)	AlN	Silicon	Diamond
Melting Point (^oC)	**2830 (2830) (sublimes)**	**2470**	**1420**	**4000 (phase change)**
Energy Gap (eV)	**2.4 (3.0)**	**6.2**	**1.12**	**5.6**
Critical Field ($\times 10^6$ V/cm)	**2.0 (2.5)**	**10**	**0.25**	**5.0**
Thermal Conductivity (W/cm-K)	**5.0 (5.0)**	**1.6**	**1.5**	**20**
Young's Modulus (GPa)	**450 (450)**	**340**	**190**	**1035**
Acoustic Velocity ($x10^3$ m/s)	**11.9 (11.9)**	**11.4**	**9.1**	**17.2**
Yield Strength (GPa)	**21 (21)**	**-**	**7**	**53**
Coeff. of Thermal Expansion ($^oC \times 10^{-6}$)	**3.0 (4.5)**	**4.0**	**2.6**	**0.8**
Chemical Stability	**Excellent**	**Good**	**Fair**	**Fair**

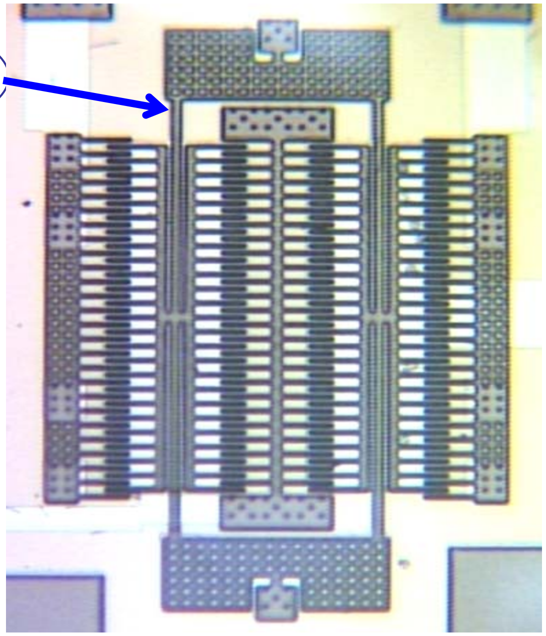
Material properties of SiC, AlN, and other semiconductor materials.

SiC Strain Sensor Development

Harsh Environment Wireless MEMS

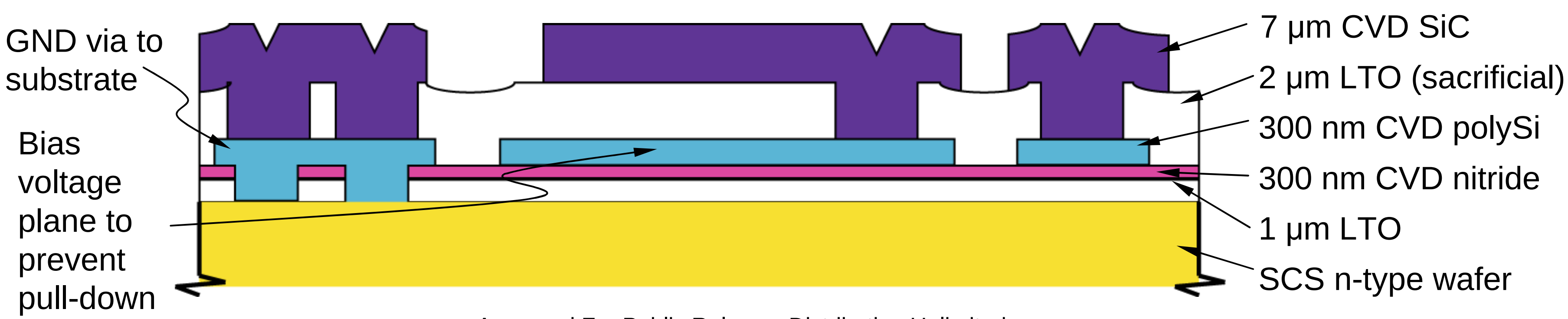


Symmetric Drive



CDDETF: the balanced DETF (BDETF)
(Second Generation)

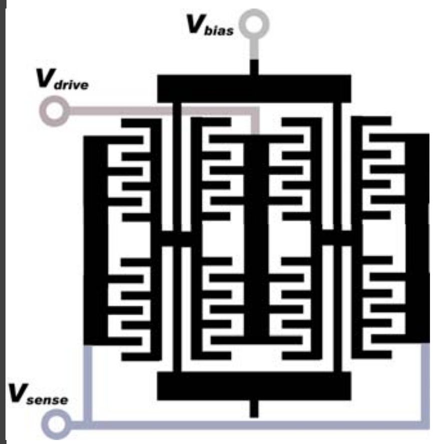
Optical micrograph of fabricated BDETF
(Second Generation)



SiC Strain Sensor Development

BSAC

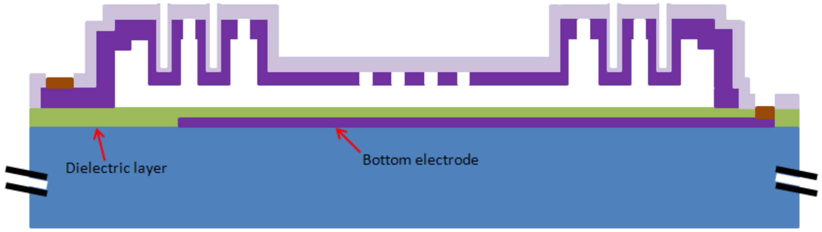
Harsh Environment Wireless MEMS



Strain Sensor

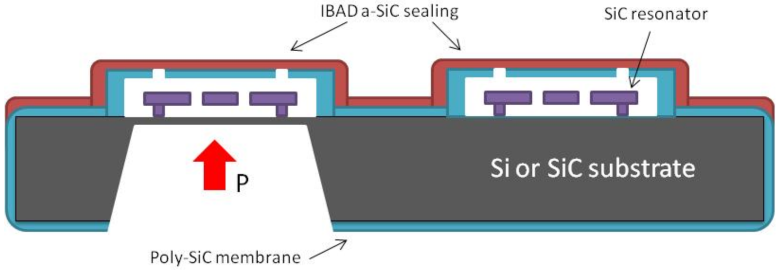
- DETF-based Strain Sensor fabricated and tested
- Resolves 0.06 με in 10 kHz bandwidth
- Operates at 600°C
- Works in dry steam environment
- Works after enduring 64,000 g
- Meets or exceeds all Phase II milestones

Accelerometer



- Design optimization in progress
- Single or Multiple shock detection
- High linearity
- Low temperature sensitivity

Pressure Sensor

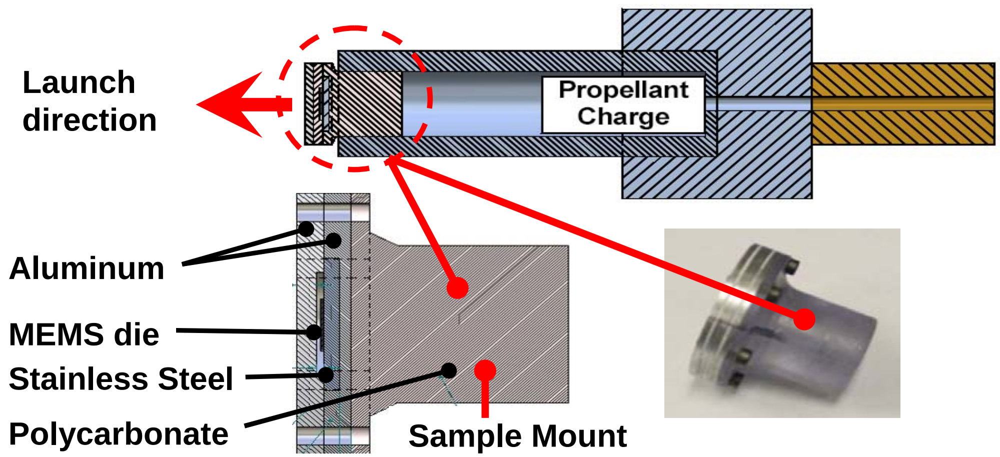


- Design optimization in progress
- Sensor based on DETF SiC strain gauge
- Diaphragm deflection strains tines
- Temperature compensation capability

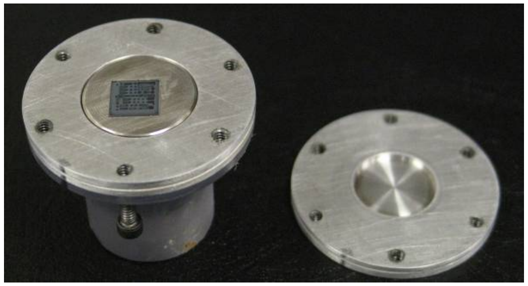
SiC Strain Sensor Shock Testing

Harsh Environment Wireless MEMS

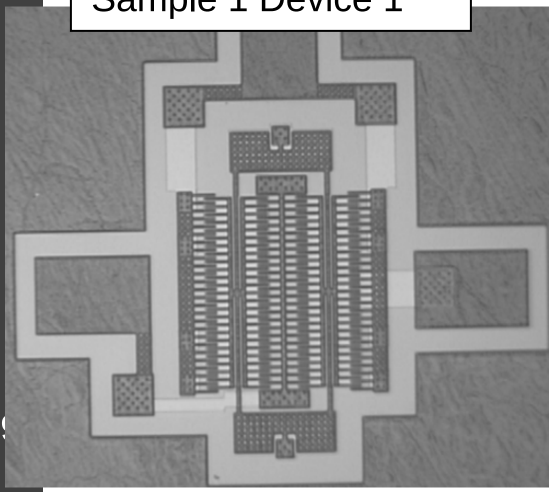
Gas Gun Schematics



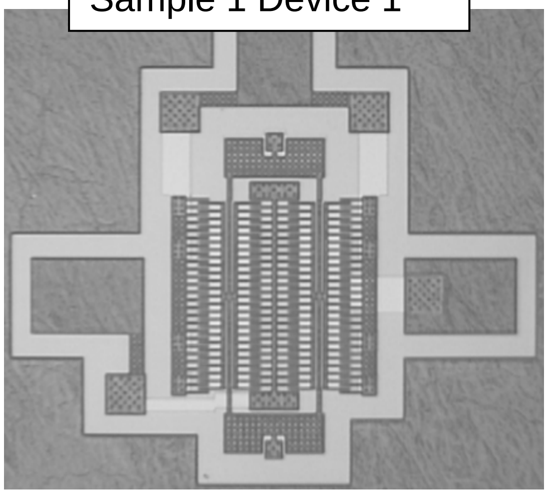
- G-shock Testing carried out at Aerophysics Research Center at University of Alabama in Huntsville
- Hard-launch soft-catch method
- Initial G-load is 64,000 g



Before G-shock
Sample 1 Device 1



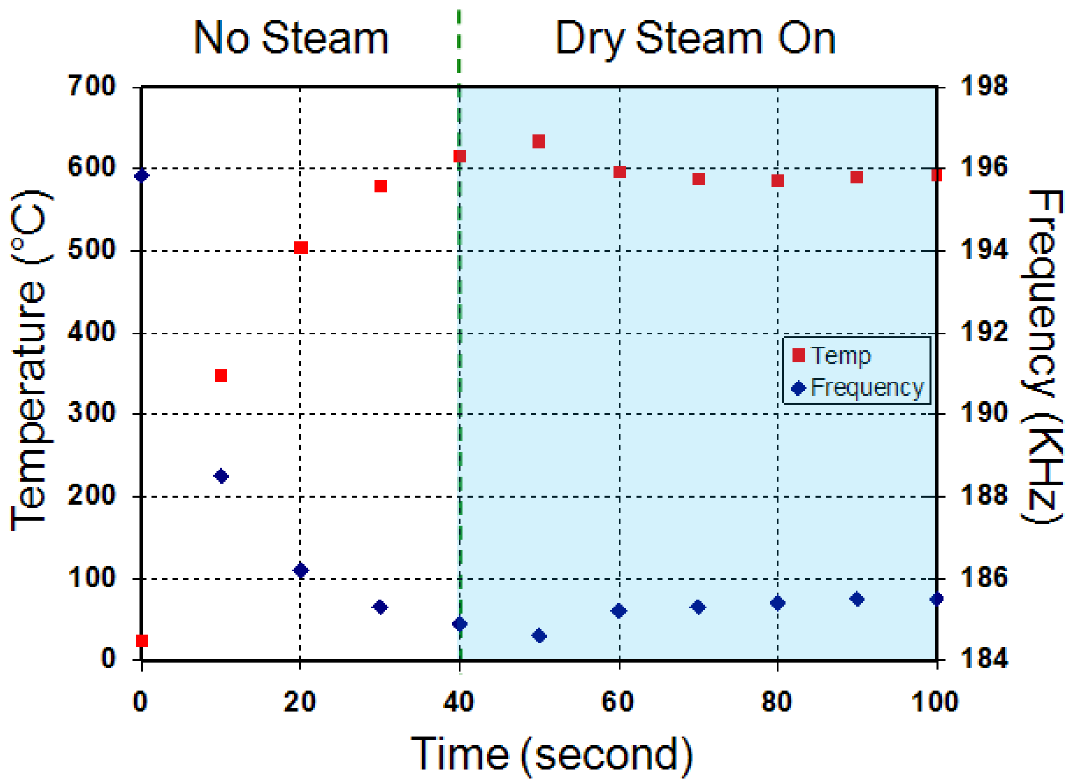
After G-shock
Sample 1 Device 1



- **No structural damage after g-shock at 64,000g**
- **Successfully operates (resonates) after enduring a 64,000 g shock**

SiC Strain Sensor at 600°C

Harsh Environment Wireless MEMS



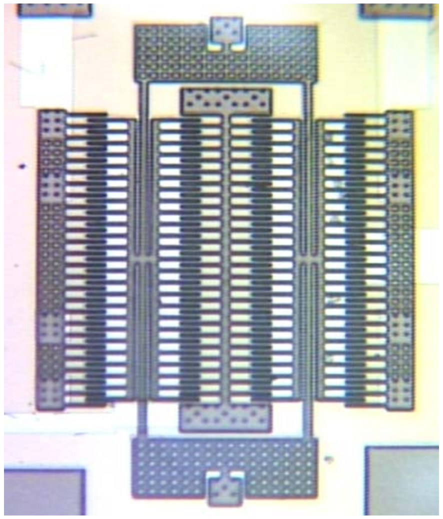


Image of SiC resonant strain sensor operated at 600 C in dry steam environment.

- **Resonant SiC strain sensor previously developed for harsh environment operation.**
- **Operation at 600 C in dry steam environment demonstrated.**
- **Operation after exposure to 64,000 G-Shock demonstrated.**

D. R. Myers et al., In review with JMM (2008)

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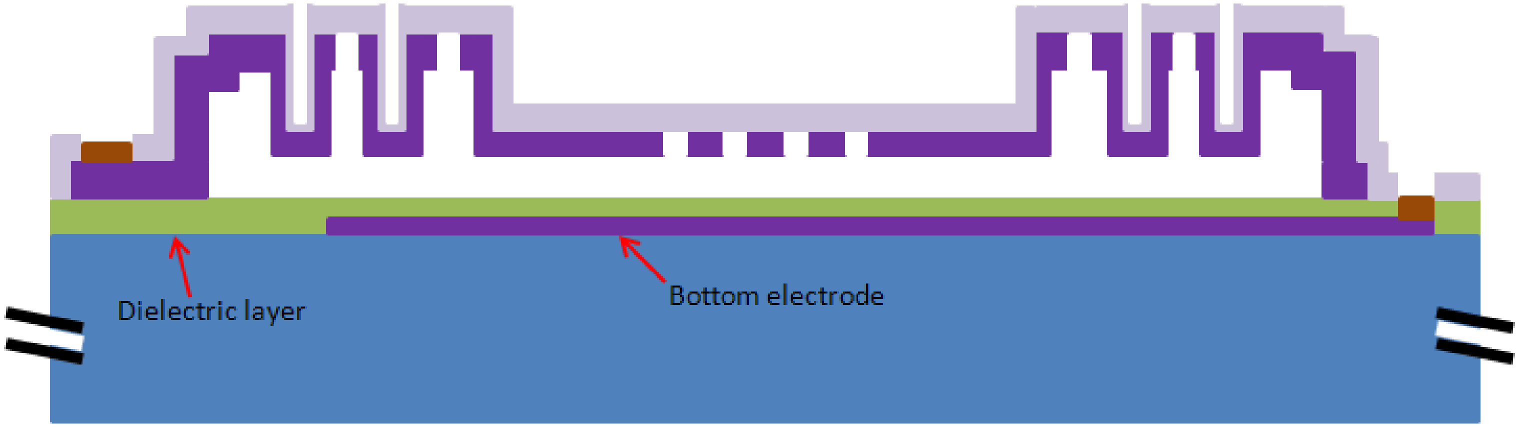
SiC Capacitive Accelerometer

Harsh Environment Wireless MEMS

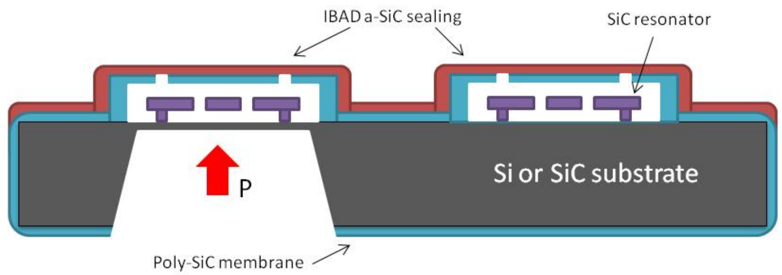


- Design optimization in progress
- Single or Multiple shock detection
- Range 5,000-100,000 g
- Sensitivity ~1 aF/g
- Resolution ~5000 g
- High linearity through corrugated diaphragm
- Low temperature sensitivity due to corrugation

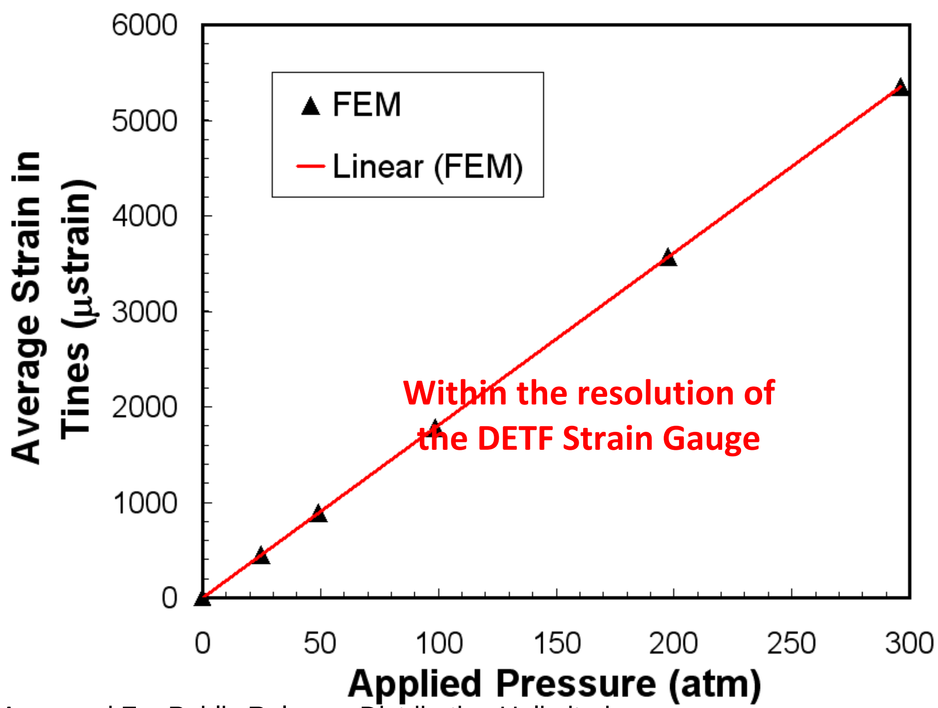
SiC Resonant Pressure Sensor

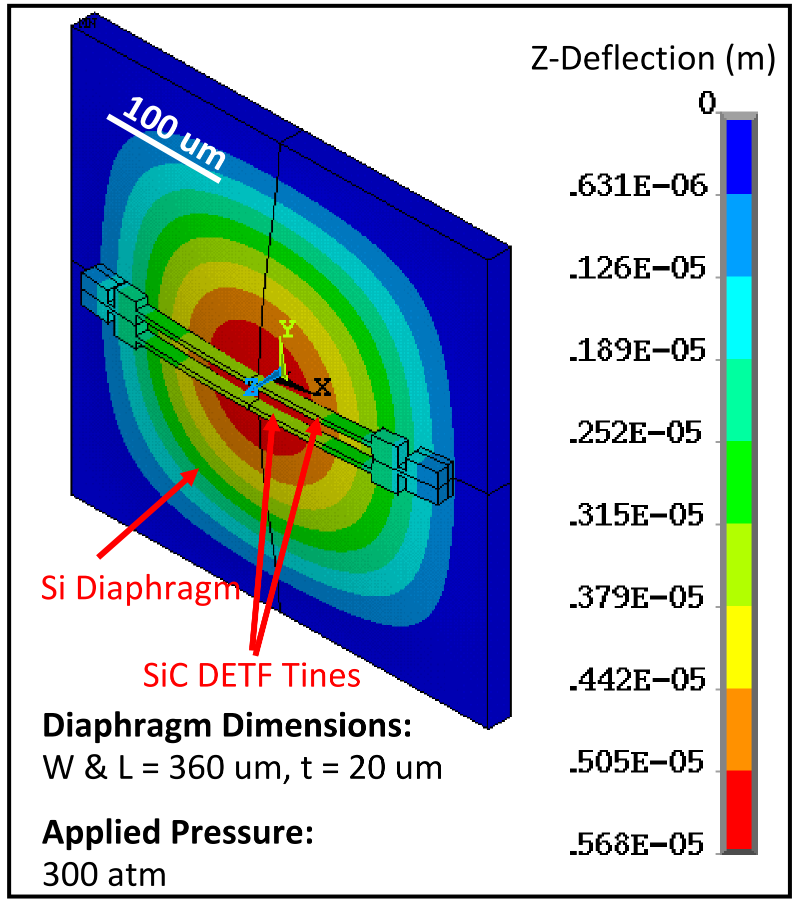
Harsh Environment Wireless MEMS

- **Design optimization in progress**
- **Sensor based on DETF SiC strain gauge**
- **Diaphragm deflection strains tines**
- **Temperature compensation capability**



Finite Element Modeling (FEM)



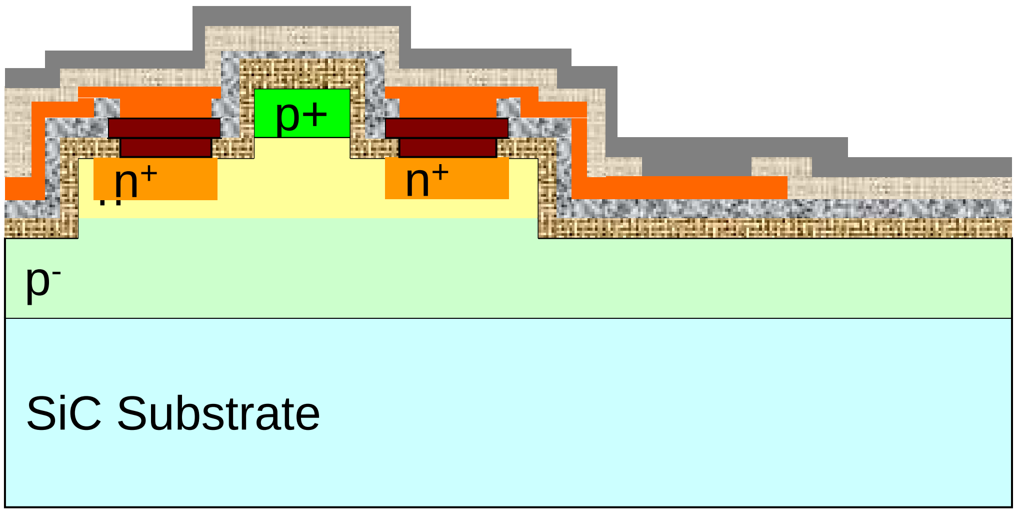


SiC Electronics Process

Harsh Environment Wireless MEMS

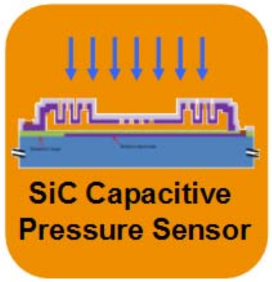
- Eight photomask steps for SiC JFET integrated circuits
- RIE etching of gate and channel layers
- Nitrogen ion implantation for ohmic metal-SiC contacts
- Thermal oxidation for surface passivation
- Multilayer metal for reliable high-T metal-SiC contacts

JFET cross-section

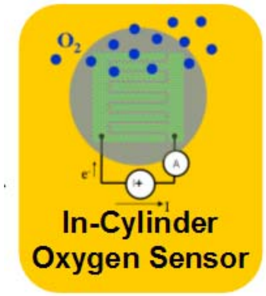


SiC Sensors in Engines

Harsh Environment Wireless MEMS



Sensor Development



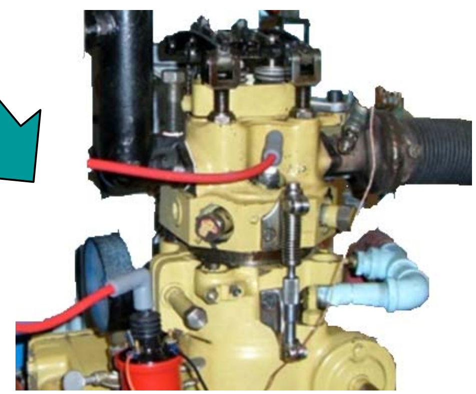
Spark Plug Sensor Mount for In-Cylinder Testing

Cellulosic Biofuel

Diesel Fuel

Glow Fuel

Fuel-Flexible, Small-Scale Engine



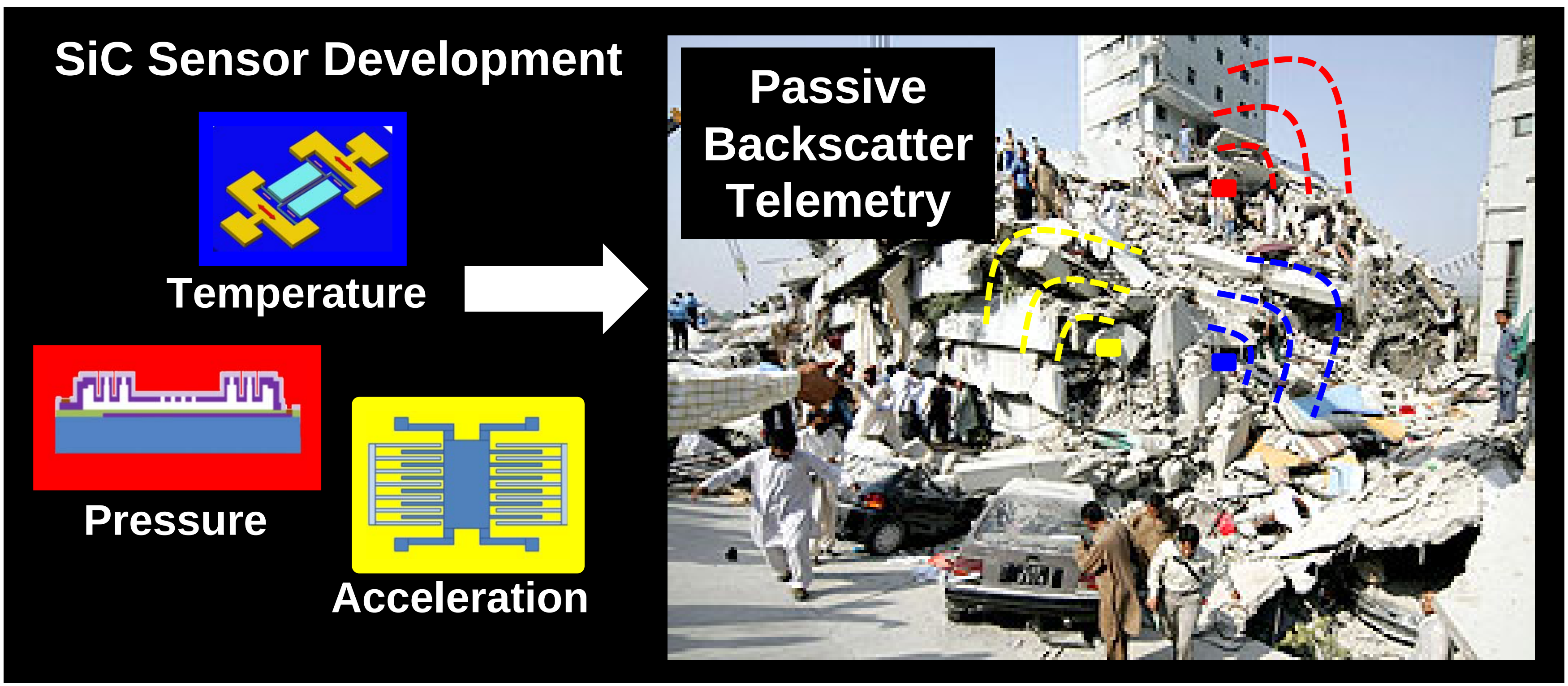
Large-Scale Combustion Fuel Research (CFR) Engine

Poster #53:
S. Wodin-Schwartz

Alternative Applications

Harsh Environment Wireless MEMS

- **Development of SiC sensors that will operate during and upon exposure to hyper extreme environments.**



LPCVD Cost Reduction

BSAC

Harsh Environment Wireless MEMS

Precursor	Purity	State	Price per gram	Price per mol of SiC	Deposition Temperature (℃)
1,3-Disilabutane*	98%	Liquid	$ 22	$ 990	750-850
Methylsilane**	99.9%+	Gas	$ 17	$ 798	750-850
Methyltrichloro-silane**	99%	Liquid	$ 0.062	$ 9.24	1000-1200

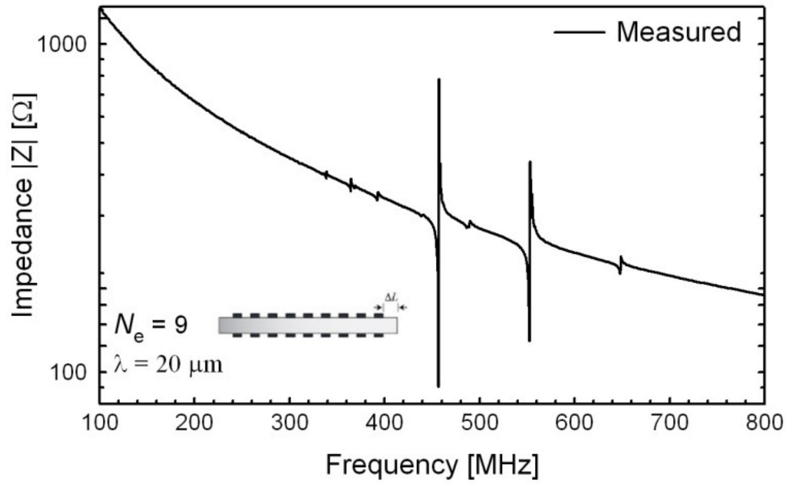
* - Current technology which previously demonstrated low stress, low resistivity films for sensor fabrication.

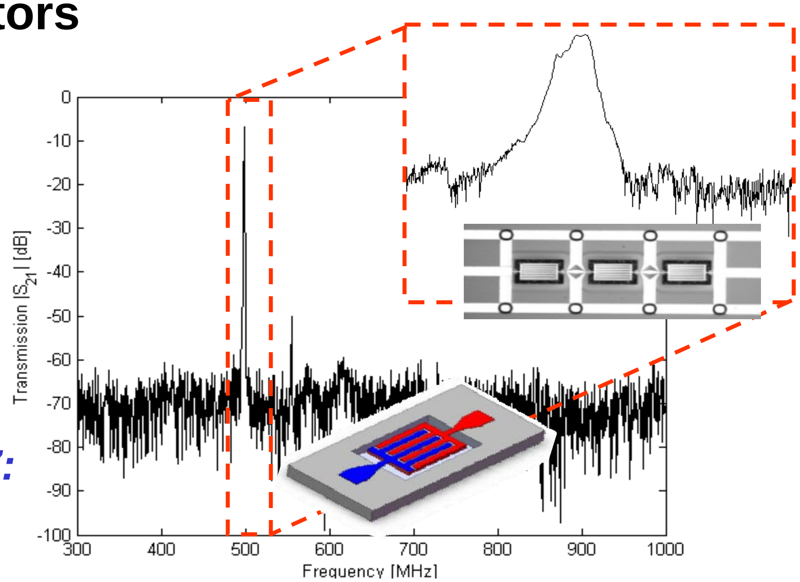
** - Proposed technology to be developed and characterized for improved cost.

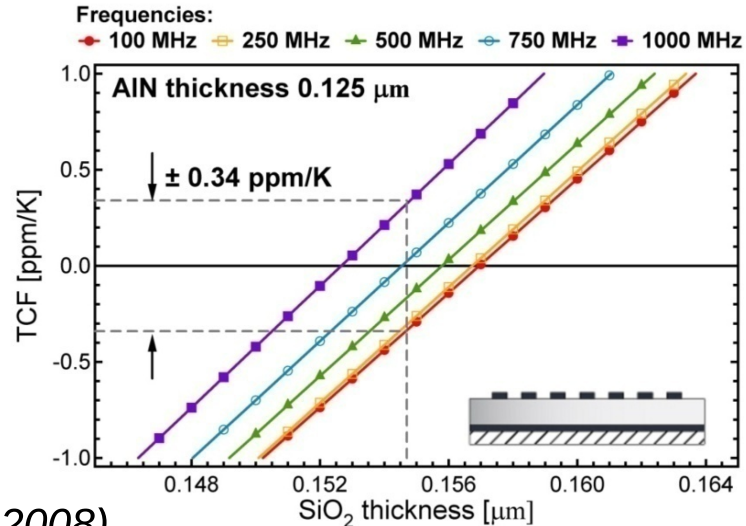
AlN for High Temperature RF

Harsh Environment Wireless MEMS

- **AlN resonators and filters demonstrated**
  - **Narrow band RF filters**
  - **Dual-mode Lamb wave resonators**
- **Temperature compensation of resonators developed**
  - **Near zero temperature compensation**
  - **Utilizes positive TCE of SiO_2 (predicted to 1200^{o}C)**
- **Developed Green's function model for resonators**





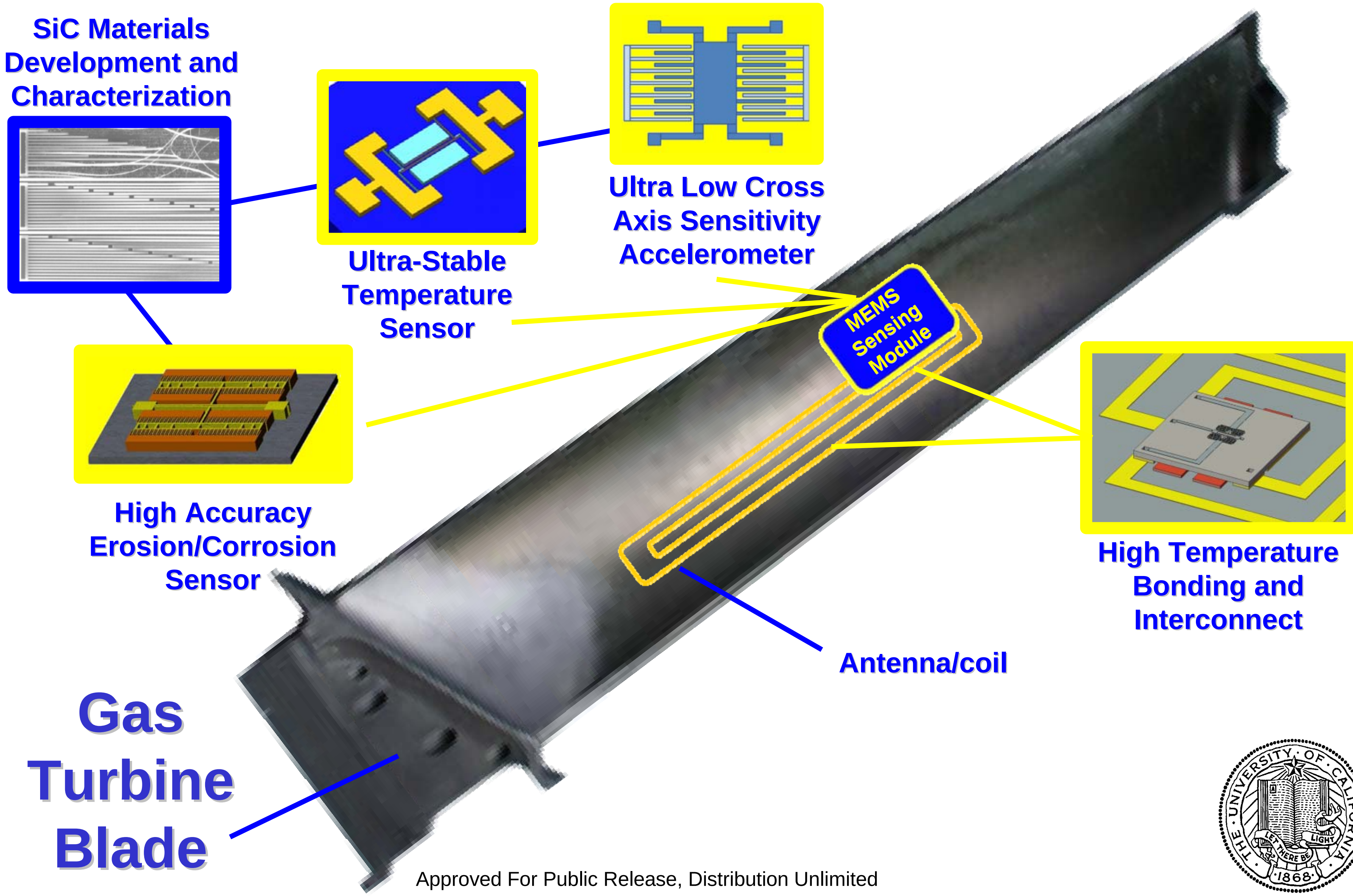


Poster #77: T.T. Yen

C.-M. Lin, T.-T. Yen, J. H. Kuypers, A. P. Pisano (2007-2008)

Future Vision 1: Passive

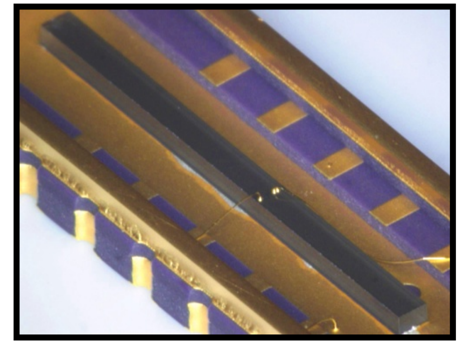
Harsh Environment Wireless MEMS

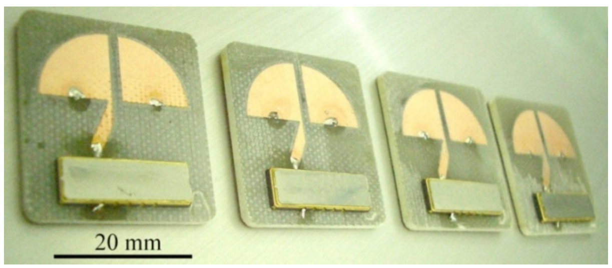


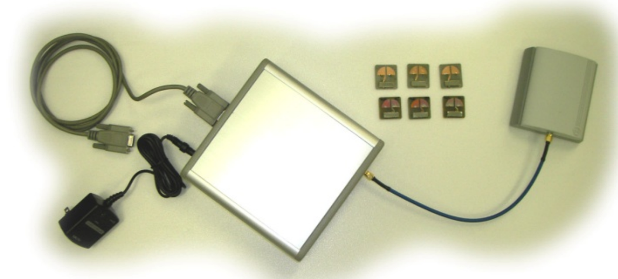
Passive Wireless Temp Sensing

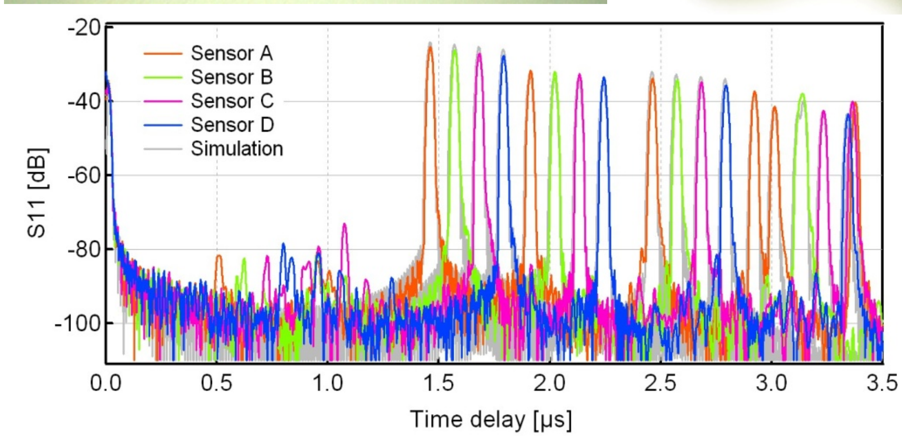
Harsh Environment Wireless MEMS

- **2.45 GHz Passive Wireless Sensor Systems**
- **Operates up to 200°C [± 0.1 °C (6σ) at SNR of 10 dB]**
- **Simultaneous readout of 4 passive sensors (→ maintanance free, no battery)**
- **Readout distance of 1-5 m (1 ms sweep time)**
- **Sensor uses surface acoustic wave on $LiNbO_3$**





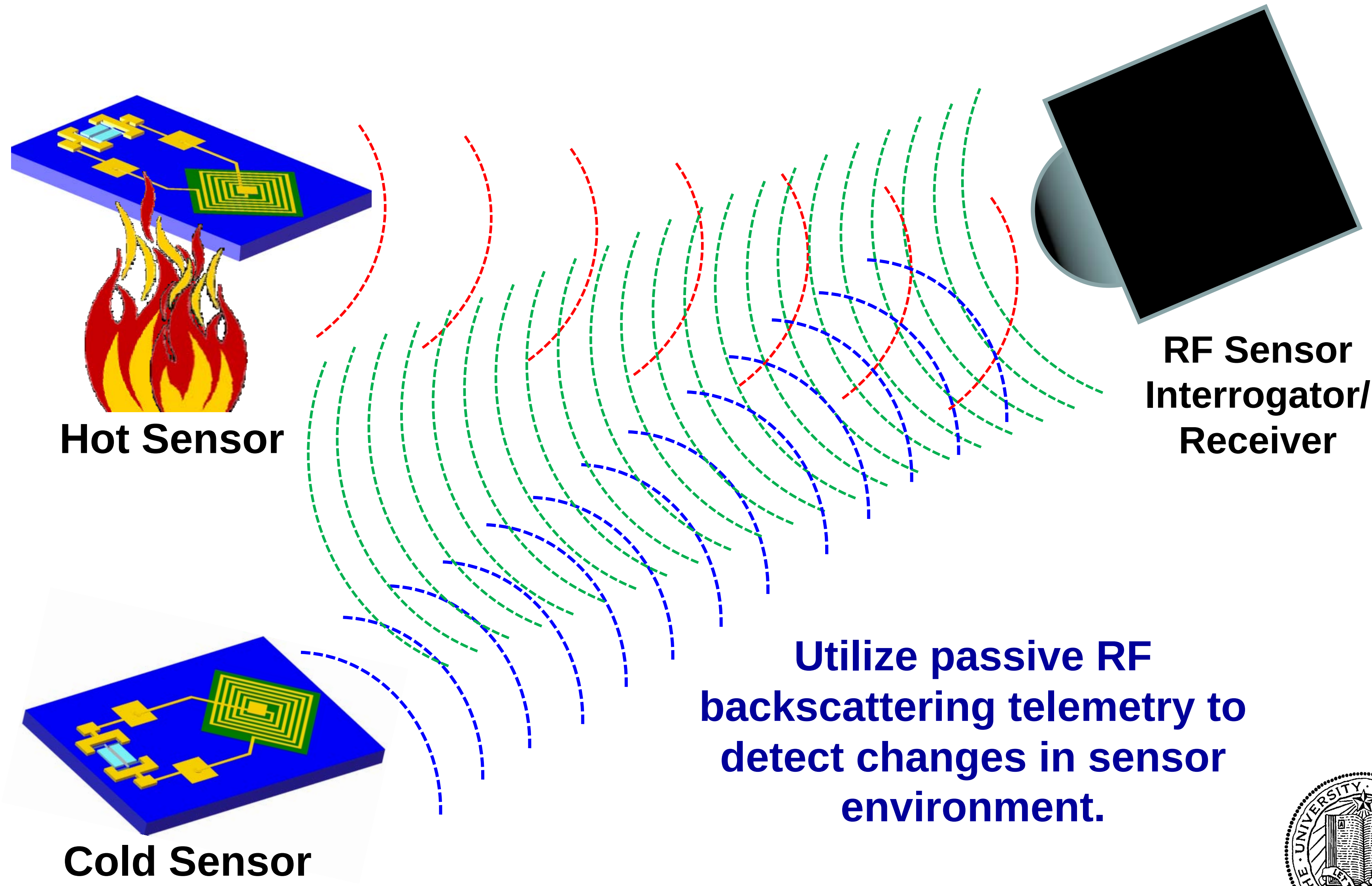




J. H. Kuypers, IUS'06, IEEE Sensors'06, Ph.D. thesis (2007)

Passive RF Backscattering

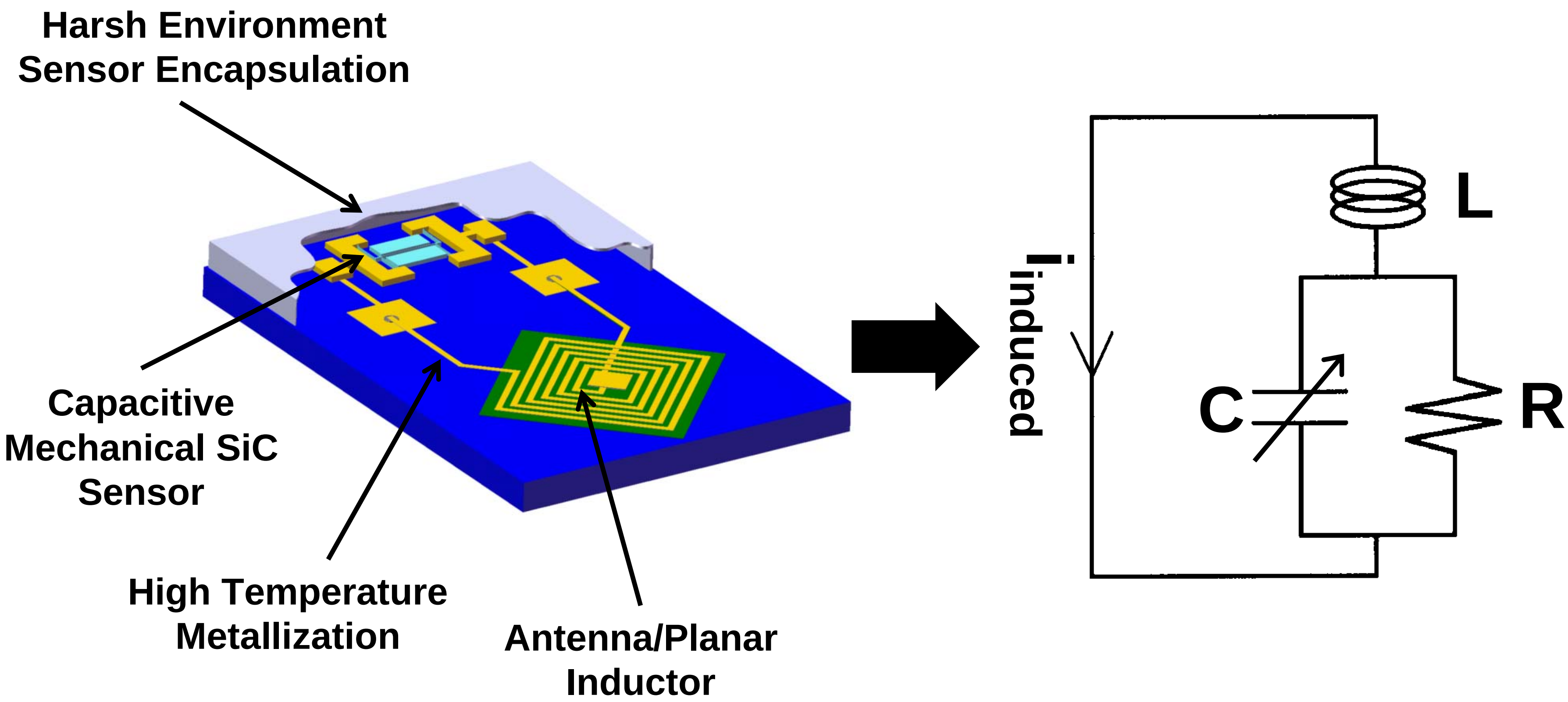
Harsh Environment Wireless MEMS



Utilize passive RF backscattering telemetry to detect changes in sensor environment.

Sensor Transduction Platform

Harsh Environment Wireless MEMS



- **Passive sensor is modeled as an RLC circuit composed of capacitive sensor (temperature, acceleration, pressure, or strain) and planar antenna.**
- **Current is induced in circuit through mutual inductance coupling between circuit and RF interrogator.**

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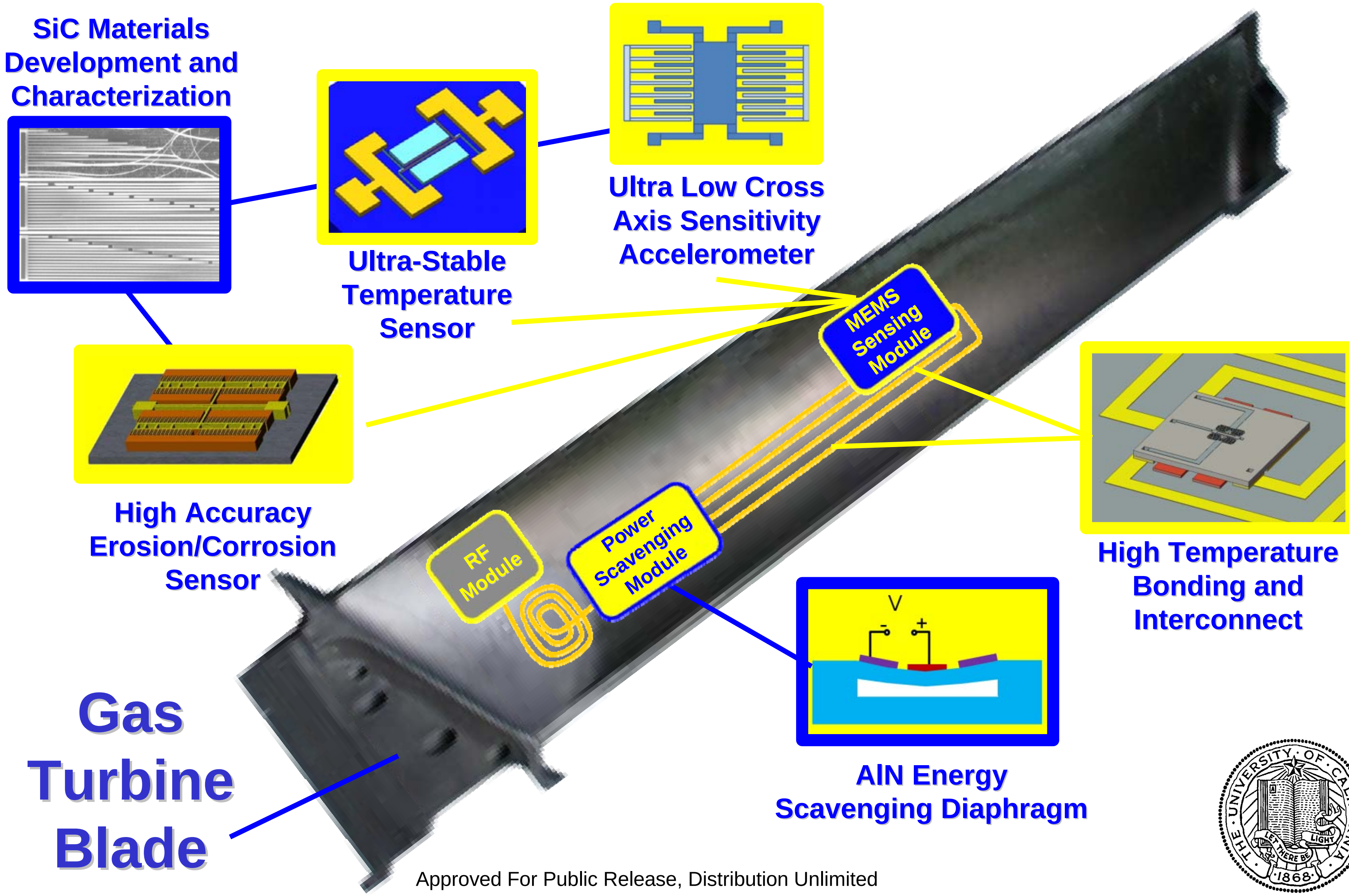
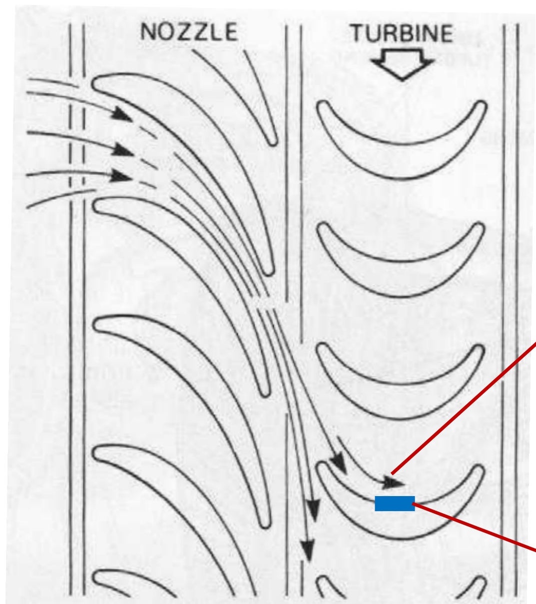
Future Vision 2: Active

Harsh Environment Wireless MEMS

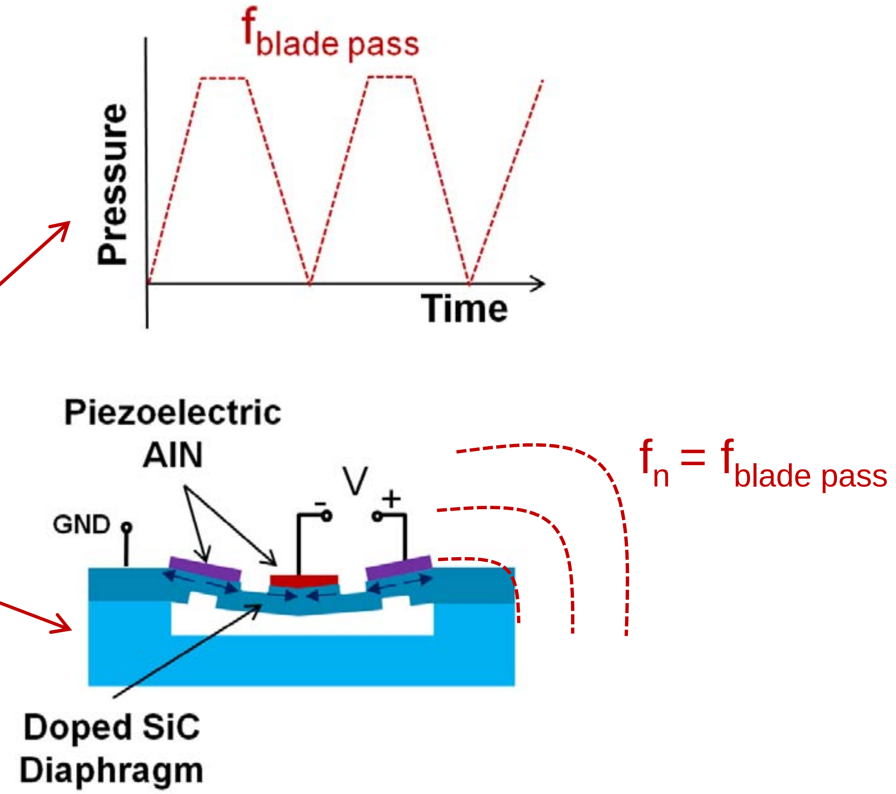


AlN Power Scavenging

Harsh Environment Wireless MEMS



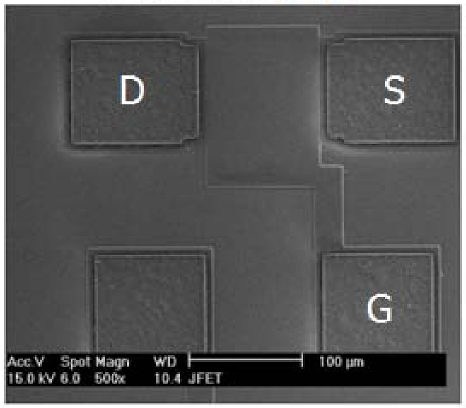
Turbine driven by impulse of gas flow (C. Soares)

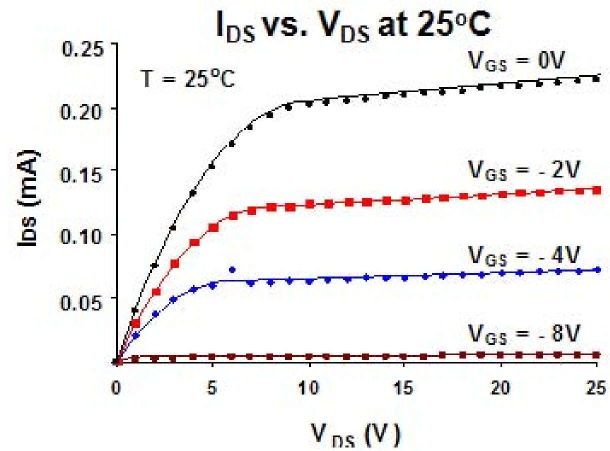


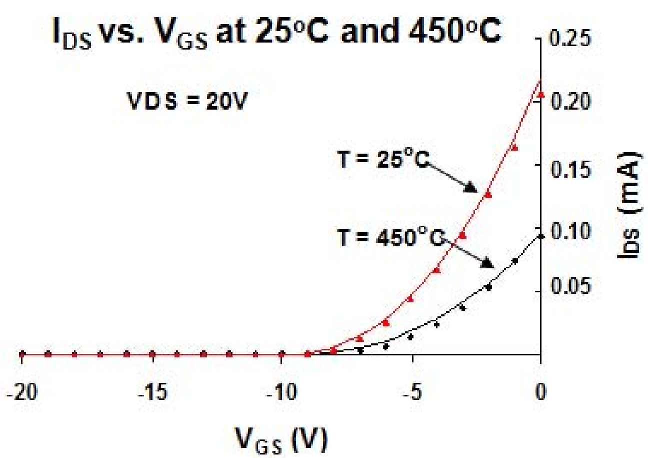
- **Utilize stable pressure pulses near turbine blade to self energize SiC diaphragm and provide power to blade sensors**
- **Design diaphragm such that the mechanical resonant frequency is matched with the blade pass frequency to maximize the output voltage**
- **May utilize rectification circuit to store voltage**

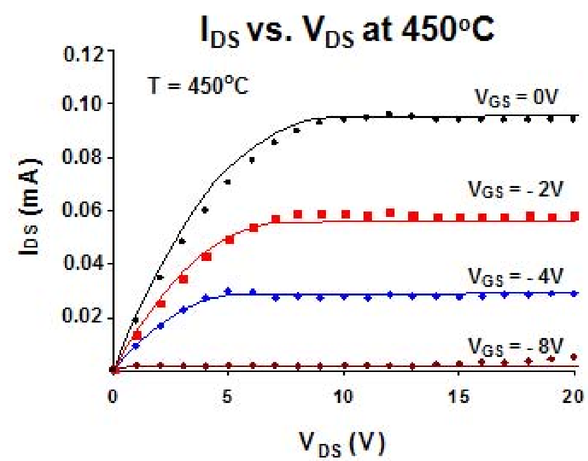
SiC JFET Operation at 450˚C

SEM Micrograph









Measured and Modeled Drain Current using 3/2-power JFET Model (W/L = 100 µm/100µm).

A. Patil, X.-A. Fu, C. Anupongongarch, M. Mehregany and S. Garverick, IEEE (2007)

High Temperature Active Platforms

BSAC

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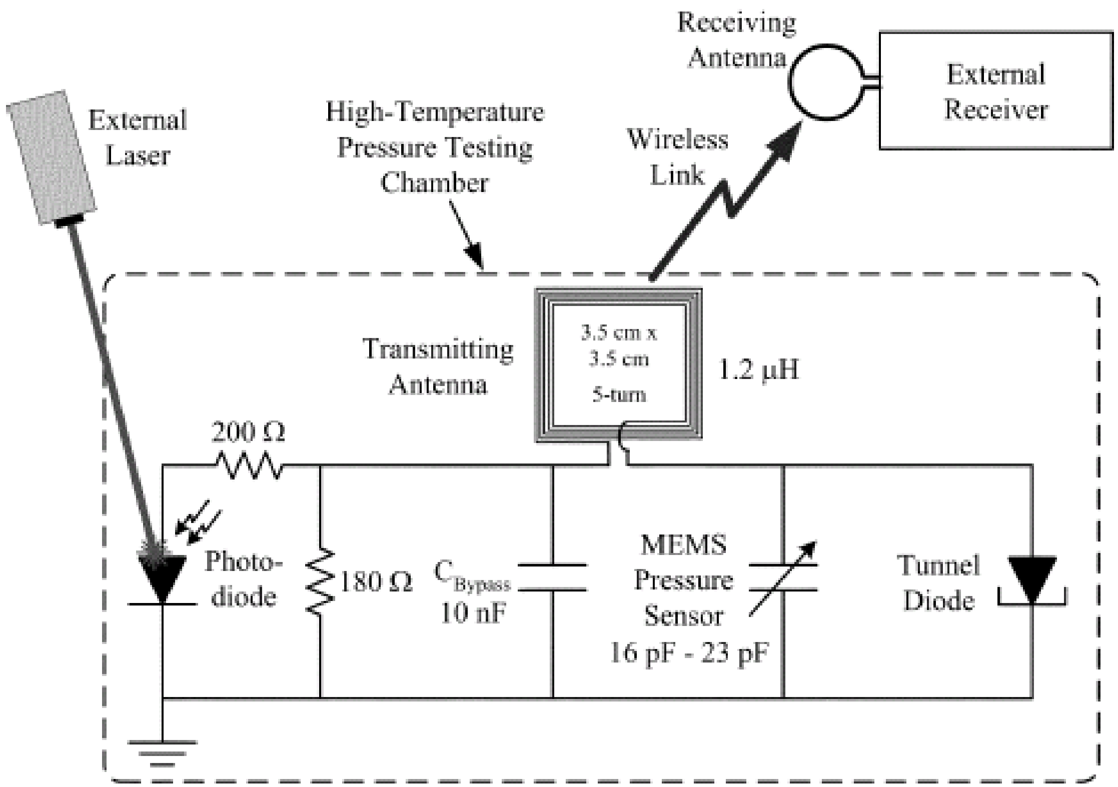
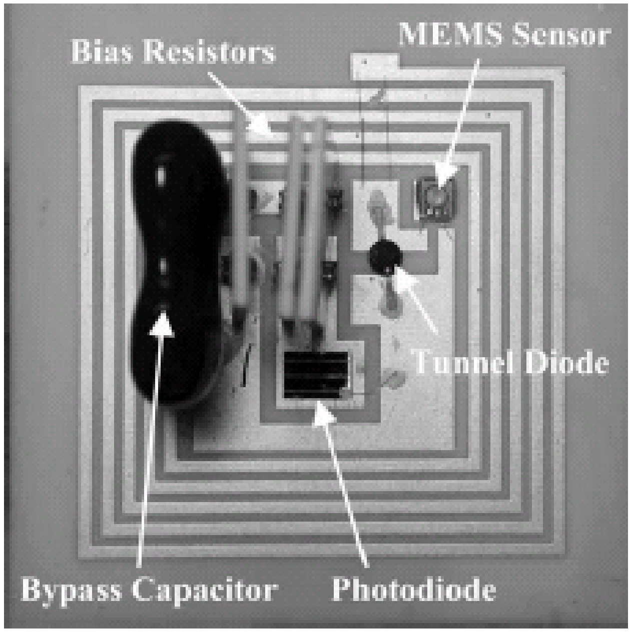




Optically powered telemetry module operated up to 250˚C over a distance of 1.5 m with a transmitter power consumption of approximately 60 µWatts.

M. Suster, W. H. Ko, and D. J. Young, JMEMS (2004)

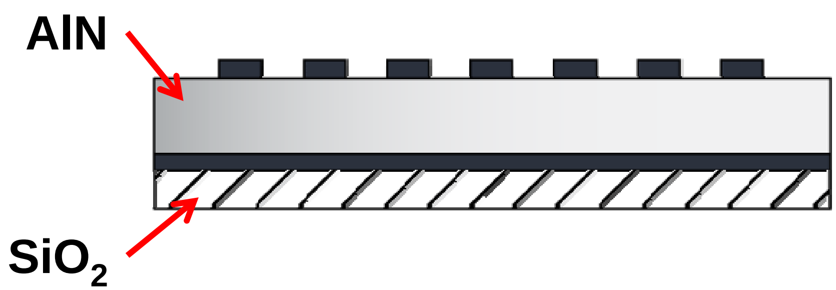
AlN Frequency References

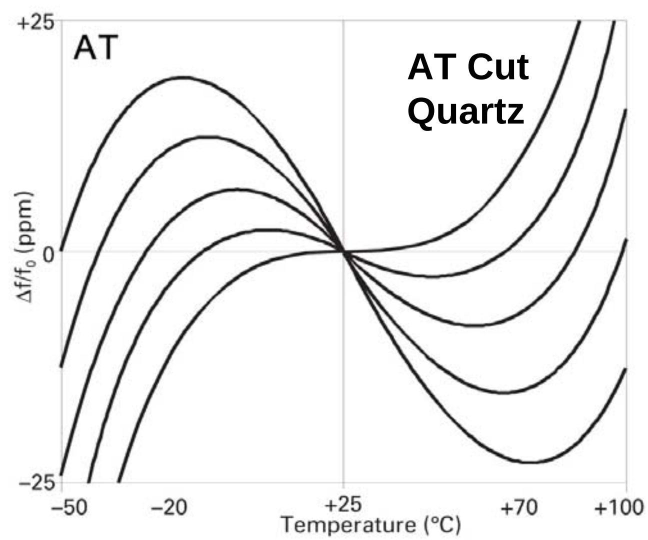
Harsh Environment Wireless MEMS

Temperature compensation of AlN Lamb wave resonators

- **Darpa S&T program**
- **Invited talk at IEEE Int. Frequency Control Symposium (May 2008)**
- **Quartz resonators only compensated around RT**

→ At BSAC: AlN resonator compensation from −270 to +600°C





Poster #78: C.-M. Lin

C.-M. Lin, G. Vigevani, J. H. Kuypers, A. P. Pisano, IEEE Freq. Contr. Symp. (2008)

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Conclusions

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- Advanced combustion energy sources (mobile and stationary) require instrumentation for increased efficiency, improved reliability, and reduced emissions.
- High-temperature SiC sensors have been developed and demonstrated in hostile environments.
- Materials such as SiC and AlN can be utilized to develop high-temperature wireless platforms.
- Two future visions (passive and active) of high-temperature transduction platforms have been presented for obtaining control data for combustion systems.
- Call for collaboration with BSAC members

Thank You!


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